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Sustainability gaps in municipal solid waste management: The case of landfills

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Sustainability gaps in municipal solid waste management: The case of landfills

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Abstract:

Our paper compares external effects of two municipal solid waste disposal technologies, bioreactor and dry tomb landfills, in a 600-year time-horizon using two different discounting techniques: Constant conventional discounting and Generation Adjusted Discounting (GAD). The paper starts with a short description of the basic characteristics of the two landfill-types. To demonstrate the sustainability deficiencies of constant discounting sustainability gaps are defined and calculated. Reference case for these calculations is the GAD which takes into account the basic requirements of sustainable development, namely intergenerational equity. Our calculations show that constant discounting usually uses too high discount rates to be in accordance with fundamental sustainability criteria leading to biased political suggestions. However, our approach is not solely restricted to landfills. It could be used as a guide to quickly check whether the results of social cost-benefit analyses of long-term public projects are in accordance with fundamental sustainability criteria.

Keywords: Generation Adjusted Discounting (GAD), constant discounting, sustainability gap, external costs, bioreactor landfill, dry tomb landfill.

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1 Introduction: Discounting and Sustainability in municipal solid waste landfills

Discounting is necessary to compare future and current monetary effects. One Euro today is – in general – worth more than the same Euro next year. Different reasons are given in the literature for positive discount rates (Ott, 2003, Bayer, 2003, Bayer, 2000). The usage of positive discount rates, however, diminishes present values of future effects which is especially the case for effects which take place in the very far future. One standard criticism against discounting is that it biases economic decisions in favour of current living generations and to the expense of future living ones which can be interpreted as an unfair and, therefore, unsustainable treatment of future generations. Discounting then even contradicts with the criterion of responsibility according to Hans Jonas (1979, see Ferrari, 2002, for a link of discounting, sustainability and the principle of responsibility) because unreflected positive discount rates almost fully “shrinks the future” (already, e.g., Pigou, 1912). Neoclassical theory favours current living generations via “high” discounting, e.g. using positive constant utility discount rates infinitely long, which – exogenously – places lower weights to effects which happen in the future. In fact, neoclassical theory imposes a moral judgement at the expense of future living generations (Ramsey, 1928). Thus, one could argue that constant discounting in neoclassical theory prevents sustainable development in general. Some philosophers demand, therefore, to refrain from discounting at all. Only in this case sustainable paths could be reached. For example, the responsibility criterion according to Jonas could be applied by setting the discount rate to zero. However, whenever there is positive growth, future living generations would be favoured at the expense of current living ones in cost-benefit analyses which is unsustainable as well. Sustainability demands that all current as well as future living generations have to be treated equally. One has to keep in mind the rationale of discounting in the very long-term: Discounting establishes a theoretical normative reference case where all affected people are ranked equally (Bayer, 2000). Both “pure strategies” – constant discounting as well as not discounting at all – neglect this criterion of equal treatment.

Economic cost-benefit analyses are generally based upon the utilitarian requirement for equal treatment of all affected individuals. Thus, the underlying assumed discounting technique must fulfil this requirement as well which can be done by employing a specific discounting procedure, the Generation Adjusted Discounting – GAD (Bayer, 2003, Rackwitz et al., 2005). In contrast to the most commonly used exponential discounting – i.e. constant discounting – technique (Koopmans, 1960, and almost all modern growth theory textbooks, e.g., Barro/Sala-I-Martin, 2004) GAD enables us to find sustainable outcomes.

Besides the intra- as well as intertemporal aspect of sustainable development, sustainable landfill management concentrates on three different general types of external costs: From the environmental side, one has to take into account the negative effects of the world-wide waste

production, i.e. environmental external costs. Waste which is a by-product of any material economic activity is unavoidable due to thermodynamic reasons (Ayres and Martinas, 1995, O'Connor, 1996). There is always a residual pollution, sometimes by means of spatial or temporal transfers. For instance, ash residues of incinerators are a dangerous waste which must be landfilled perhaps infinitely-long (Hellweg et al., 2000). The external costs may occur in the remote future (e.g., greenhouse effect of methane emissions for anaerobic processes, leakage of leachate in the soil and the groundwater) which has to be considered in a social cost-benefit analysis. Managing waste is also a very difficult task because everybody is producing waste and nobody wants to have it in his backyard. Disamenity costs have also to be taken into account as external costs for a comprehensive analysis allowing for a socially accepted management of waste.

The paper is organized as follows: We start with assigning external effects of two different types of landfills, i.e., the dry tomb technology and the bioreactor type for municipal solid waste disposal (section 2). This is followed by considering the intertemporal aspect via discounting external effects to the planning horizon according to Generation Adjusted Discounting (GAD) and a comparison with outcomes using constant discounting (section 3). In section 4 we define a "sustainability gap", calculate some examples, and demonstrate that constant discounting could have a significant unsustainable character. Some political suggestions as well as a general outlook are given at the end.

2 The specific case of landfills

Most of waste treatment activities have to deal only with flows of materials. In contrast, landfills have also to cope with stocks of materials which are infinitely-long in direct physical contact with the soil and possibly water. These peculiarities lead to fears of human-beings with respect to the ability of the landfills – independent of the state of technological progress (complementary or even redundant mineral and man made synthetic barriers) – to protect the whole environment from (potential) damages caused by any pollutant flow at all points in time. These potential flows are due to the high chemical gradient between their internal content and the environment (Ayres and Martinas, 1995). This is the reason why landfills are one of the most important problems in waste management with respect to the implementation of sustainability criteria, which has already been addressed by Page (1988). Moreover, many studies show that – for example – solely the disamenity costs at stake are quite high (Faber, 1998, COWI, 2000, DEFRA, 2003, MEDD, 2005). There are intratemporal locational choice problems, too, possibly leading to rivalries in the usage of soil. In many developed countries newly planned as well as established municipal solid waste landfills lead to possibly costly conflicts in some regions (Barbier and Waechter, 2001).

Landfills can be distinguished in sanitary landfills (municipal solid waste), hazardous waste landfills and nuclear waste landfills. We concentrate – exemplary – on the first type of landfills in this paper. It is the most common in the world. Most of all countries use sanitary landfills for more than fifty percent of their municipal solid waste (ISWA, 2006). The potential damage of the waste mass will strongly decrease in less than one century if enough water is filled into the landfill to enhance the anaerobic degradation of the waste. But an enormous time lag has to be taken into account as well due to the time transfer of pollutants into the soil and the ground water which may last many centuries (Méry, 2005).

There are two main technologies in sanitary landfilling: The dry tomb technology (or passive landfill) where the waste mass degrades anaerobically in about half a century. It contains a risk of pollution which may occur during many decades while the protective barriers may fully or partly degrade. The bioreactor technology (or active landfill) aims at accelerating the anaerobic process to reduce potential pollution more rapidly by an active management of the liquid content of the waste mass (Vigneron, 2005). When the bioreactor technology is implemented, the external costs are more concentrated in the present compared to the dry tomb technology. Thus, the bioreactor technology has not the same potential to affect future generations with high long-term external costs as it is the case in the dry tomb technology.

Besides the efficiency aspect an argument of justice is relevant as well: When the bioreactor technology is implemented each generation would be able to cope with their own external costs instead of producing intertemporal external costs for future living individuals. Méry and Bayer (2005) show that the bioreactor-type landfills are more sustainable – i.e. efficient as well as fair – compared to the dry tomb-type especially when there are very low growth rates in the economy in a 600-year context (up to 1% p.a. real consumption growth). Additionally, although several studies with respect to external costs of landfills emphasize that long-term effects have to be taken into account, there is a danger that current environmental laws in different world regions underestimate the real damages by demanding only a thirty years post-closure survey which is the case in the European Union and the U.S.A (European Commission, 1999, U.S. EPA, 1991).

All these considerations show that the length of the time horizon has to be carefully chosen in order to capture all external effects caused by the emissions of landfills. The current state of knowledge requires an extension of the horizon for our analysis as long as physical effects could occur which automatically leads us to an intergenerational setting of many centuries (see Méry and Bayer, 2005). Thus, the question of discounting becomes of highest relevance.

3 Generation Adjusted Discounting

Discounting has major impacts on the results and, of course, on the political suggestions of cost-benefit analyses. Constant exponential discounting with one single constant rate factually

defines the above worked-out landfill-problems away in present value terms. Long-term impacts would not play any role in this discounting regime. We, therefore, apply another discounting technique, the GAD, which allows more sustainable statements even in these long time horizons which are of relevance for the landfill case.

3.1 General Framework

The innovation of GAD is to differentiate between intra- and intergenerational discounting with two different discount rates. For calculating intragenerational, generation-specific present values, all effects during the respective individuals' lifetimes have to be discounted to the beginning of the lives of these individuals by applying their respective individual time preference rate. Intragenerational present values can be easily interpreted as generational accounts. The intragenerational discount is given as the sum of the pure time preference rate (pure time preference rate PTPR) and the growth time preference rate (growth time preference rate GTPR): $\delta = \rho + \varepsilon g$, which is exactly the well-known Euler-equation. As is common, ρ represents the individual discount rate which depicts individual myopia and/or impatience. Due to ethical reasons, it can only be relevant for calculating individual (or in our case generation-specific) present values (Ramsey, 1928, Bayer, 2000, 2003). The product of the real growth rate g (per capita and per generation) and the elasticity of marginal utility with respect to consumption ε equals the growth-time preference rate. We want to assume – in accordance with most of the economic models using CRRA-utility functions – that ε is unity. To calculate intergenerational present values, all intragenerational present values have to be once again discounted to the beginning of the planning time t_0 of the whole project. However, to treat all generations equally, intergenerational discounting from the beginning of the lifetime of each generation to t_0 need not consider aspects of myopia and/or impatience. From a social point of view, they differ only in their respective level of consumption which has to be taken into account by growth discounting according to decreasing marginal utility (“intergenerational discounting”). In table 1, the dark shaded area shows these time periods, where intergenerational discounting has to take place to determine a social present value at the beginning of our plans of action. Therefore, only the intergenerational discount rate – the real growth rate – can be used for equity reasons.

Generation	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}	t_{13}	$\dots t_n$
A	c_0														
B	c_0	$c_1 \cdot \theta^{-1}$													
C	c_0	$c_1 \cdot \theta^{-1}$	$c_2 \cdot \theta^{-2}$												
D	c_0	$c_1 \cdot \theta^{-1}$	$c_2 \cdot \theta^{-2}$	$c_3 \cdot \theta^{-3}$											
E	c_0	$c_1 \cdot \theta^{-1}$	$c_2 \cdot \theta^{-2}$	$c_3 \cdot \theta^{-3}$	$c_4 \cdot \theta^{-4}$										
F	c_0	$c_1 \cdot \theta^{-1}$	$c_2 \cdot \theta^{-2}$	$c_3 \cdot \theta^{-3}$	$c_4 \cdot \theta^{-4}$	$c_5 \cdot \theta^{-5}$									
G	c_0	$c_1 \cdot \theta^{-1}$	$c_2 \cdot \theta^{-2}$	$c_3 \cdot \theta^{-3}$	$c_4 \cdot \theta^{-4}$	$c_5 \cdot \theta^{-5}$	$c_6 \cdot \theta^{-6}$								
H	c_0	$c_1 \cdot \theta^{-1}$	$c_2 \cdot \theta^{-2}$	$c_3 \cdot \theta^{-3}$	$c_4 \cdot \theta^{-4}$	$c_5 \cdot \theta^{-5}$	$c_6 \cdot \theta^{-6}$	$c_7 \cdot \theta^{-7}$							
I		c_1	$c_2 \cdot \theta^{-1}$	$c_3 \cdot \theta^{-2}$	$c_4 \cdot \theta^{-3}$	$c_5 \cdot \theta^{-4}$	$c_6 \cdot \theta^{-5}$	$c_7 \cdot \theta^{-6}$	$c_8 \cdot \theta^{-7}$						
J			c_2	$c_3 \cdot \theta^{-1}$	$c_4 \cdot \theta^{-2}$	$c_5 \cdot \theta^{-3}$	$c_6 \cdot \theta^{-4}$	$c_7 \cdot \theta^{-5}$	$c_8 \cdot \theta^{-6}$	$c_9 \cdot \theta^{-7}$					
K				c_3	$c_4 \cdot \theta^{-1}$	$c_5 \cdot \theta^{-2}$	$c_6 \cdot \theta^{-3}$	$c_7 \cdot \theta^{-4}$	$c_8 \cdot \theta^{-5}$	$c_9 \cdot \theta^{-6}$	$c_{10} \cdot \theta^{-7}$				
L					c_4	$c_5 \cdot \theta^{-1}$	$c_6 \cdot \theta^{-2}$	$c_7 \cdot \theta^{-3}$	$c_8 \cdot \theta^{-4}$	$c_9 \cdot \theta^{-5}$	$c_{10} \cdot \theta^{-6}$	$c_{11} \cdot \theta^{-7}$			
M						c_5	$c_6 \cdot \theta^{-1}$	$c_7 \cdot \theta^{-2}$	$c_8 \cdot \theta^{-3}$	$c_9 \cdot \theta^{-4}$	$c_{10} \cdot \theta^{-5}$	$c_{11} \cdot \theta^{-6}$	$c_{12} \cdot \theta^{-7}$		
N							c_6	$c_7 \cdot \theta^{-1}$	$c_8 \cdot \theta^{-2}$	$c_9 \cdot \theta^{-3}$	$c_{10} \cdot \theta^{-4}$	$c_{11} \cdot \theta^{-5}$	$c_{12} \cdot \theta^{-6}$	$c_{13} \cdot \theta^{-7}$	
\vdots								\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\ddots

Table 1: Intragenerational effects in an 8-Generation-Model, $\theta \equiv (1+\delta)$.

The application of GAD requires some simplifying assumptions. These assumptions are one possible application of GAD. All effects which take place in a specific time period are equally divided between all the then living generations. Additionally, all external effects influence all individuals' consumption. Whenever the external effects would influence investment units, we have to calculate consumption equivalents to deal with that problem (Bayer, 2003, 2004). We calculate present values in decadal steps assuming that all generations live exactly for 8 decades. This sufficiently represents the average life expectancy in the industrialized countries, which is our assumed framework. Thus, at each point in time, 8 simultaneously living generations of different age exist. At the end of each decade, the oldest generation dies and a new generation is born. At the beginning of our planning horizon, t_0 , eight generations exist which are affected by equally distributed external effects. At the end of time period t_0 , the oldest generation A dies and a new generation I is born, which lives up to time period t_8 . The rest proceeds analogously.

GAD works as follows: Up to generation H the discounting process is in exact accordance with the Euler-equation ($\delta = \rho + \varepsilon g$). Thus, the generation-specific intragenerational present values can be added up to determine a social present value for all generations living in the time period when the analysis begins (t_0). Beginning with time period t_1 up to the end of the planning horizon the discounting process has to be adjusted due to the utilitarian requirement of equal treatment of all affected generations: Firstly, intragenerational present values have to be calculated which refer to the beginning of the lifetimes of all the then living generations. Afterwards, these generational accounts have to be discounted to the planning time t_0 solely using the growth rate (intergenerational discounting). Thus, whenever a positive myopic

discount rate (ρ) is used, GAD uses lower intergenerational discount rates compared to intragenerational ones and the difference between the two rates is exactly the myopic discount rate.

Mathematically, the formula for calculating present values according to GAD is given as follows:

$$(1) \quad PV_{GAD} = \sum_{j=0}^{L-1} (L-j) \cdot \frac{c_j / G_j}{(1 + \rho_j + \varepsilon_j \cdot g_j)^j} + \sum_{\ell=1}^{PH} \frac{\sum_{i=\ell}^{\ell+(L-1)} \frac{c_i / G_i}{(1 + \rho_i + \varepsilon_i \cdot g_i)^{i-\ell}}}{(1 + \varepsilon_\ell \cdot g_\ell)^\ell},$$

mit $c_i, c_j = 0$ für alle $i, j > PH$.

PH symbolizes the planning horizon of the analyzed project and L represents the life expectancy of each generation (8 decades). G is the number of generations living at the same time (8 generations are living simultaneously). All periodical project-induced consumption effects (c_i, c_j, c_ℓ) are assumed to be equally distributed between all then living generations. The variables j, i , and ℓ are used as time indices.

The first summand describes all intragenerational consumption effects which appear in the planning period for all presently-living generations. The longer the planning horizon is extended, the less important becomes this term. The fracture in the numerator (right summand in equation (1)) expresses all intragenerational consumption effects of all generations born after the planning period t_0 . These intragenerational effects are discounted to the beginning of the lives of each respective generation only. All generations are allowed to employ the sum of the PTPR and the GTPR as their relevant discount rates. However, intragenerational present values have to be once again discounted with the term in the denominator of the fraction on the right-hand side of equation (1): $(1 + \varepsilon_\ell \cdot g_\ell)^\ell$. The relevant discount rate is the GTPR (intergenerational discounting). At last, we have to consider that intragenerational as well as intergenerational effects possibly occurring after the end of the planning horizon cannot be taken into account in our calculations. Therefore, consumption effects c_i and c_j with $i, j > PH$ have to be set to zero.

Equation (1) shows that GAD does not require constant intra- as well as intergenerational discount rates. Whenever it would be necessary, these rates can vary for each time-period i, j , and ℓ . Thus, behavioral considerations with respect to hyperbolic discounting could easily be adopted into the GAD which is interesting especially for intragenerational discounting (Frederick et al., 2002).

The most important GAD-effect is the convergence of the long-term discount rate towards the growth time preference rate. Thus, the factual periodical discount rate decreases from the sum of the myopic and the growth time preference rate to the growth time preference rate which causes significant effects with respect to present value calculations. The pure time preference rate is not that significant as it is in the constant discounting regime because its impact almost fully disappears (Rackwitz et al., 2005).

One criticism against the usage of GAD is that it leads to intertemporal inconsistencies – like all discounting procedures which are not exponential (Strotz, 1955/56). This refers mainly to first-best-models. However, in a first best world all external costs have been internalized to the polluters. No biasing effects on prices, and, of course, on demand and supply do exist at all. Whenever we analyze external effects which are not internalized to the polluters, we automatically argue in a second-best world (Faucheux et al., 1998, Asheim, 1994) where prices are biased and do not show the market-shortages correctly. Goods and services which are produced or consumed with high external costs are oversupplied whereas goods and services which have external benefits are not sufficiently supplied compared to the optimal, i.e. first-best, market volume. And, of course, in second best worlds the argument of time-consistency according to Strotz does not play any role because the assumed “rational” way of planning cannot be realized due to the non-constant set of choices. Additionally, from a practical perspective in democracies, time consistency cannot play any decisive role because of the possibility of governmental changes after elections and, possibly, a radical change in the political direction. It is obvious that these effects can only be accidentally time-consistent and usually these types of political changes are highly time-inconsistent (Bayer, 2000, pp. 154-157, Méry, 2005, pp. 88-94).

Besides efficiency and equity, the necessity of intertemporal consistency is an additional topic which might be in conflict with the two former arguments. Efficient solutions need neither to be time consistent nor fair and the opposite is also valid: fair solutions need neither to be efficient nor time-consistent and so on. One may consider that the deficiency of time-inconsistency of the GAD is (at least) qualitatively compensated by the fulfilment of equal treatment of all affected generations. Thus GAD produces efficient and fair results with the lack of time-consistency. Especially in second-best models the overall net gain of offering fair and efficient results at the expense of time-consistency is quite close to a Pareto-improvement.

3.2 Present Value Calculations – Results

GAD is applied to a data set which is in more detail explained and derived in Méry and Bayer (2005). The exact external costs of a typical bioreactor- and a dry-tomb-landfill are given in Annexes A1 and A2. To capture uncertainties with respect to the intragenerational as well as

the intergenerational discount rate we assume a range of possible rates according to major publications on these figures. The individual discount rate (PTPR) is strictly assumed to be positive, which is in accordance with general findings (for some exemptions see, e.g., Loewenstein and Prelec, 1992, Price, 1993): $0.5\% \leq \text{PTPR} \leq 4.5\%$. The intergenerational discount rate (GTPR) is assumed to range from $-1\% \leq \text{GTPR} \leq 3\%$. These figures can be observed in European history and, more general, could be legitimated when concentrating on effects which completely take place in industrialized countries. But GAD does not require the application of these assumptions. It can be used in developing countries as well, where we have to increase both rates. Thus, the application of GAD is not limited to our specific examples.

We assume a time horizon of 600 years. At the one hand, we have to consider at least half a millennium to integrate all plausible environmental impacts in the analysis (INVS, 2004, Méry and Bayer, 2005). On the other hand, the time horizon should not predetermine the results of our comparison of the external costs of bioreactor and dry tomb landfills. Sensitivity calculations with shorter time horizons show that up to 400 years planning horizon, some of our results in the 600 year context could not be confirmed. Starting with 500 years time horizon, the results are not time sensitive any more. Arguing conservatively, we extend the assumed time horizon to 600 years to be sure that the time-sensitivity of our results does not bias them towards the one (bioreactor) or the other direction (dry tomb). Extending the time horizon beyond 600 years does not make any sense for our comparison since the general trend of the efficiency of dry-tomb- and bioreactor-landfills is not reversed.

We exemplary concentrate on the best guess case. The results of the two others cases (best case, worst case) are given in the Annexes B1 and B2. For simplifying our analysis, we calculated all present values in decadal steps, and, of course, the yearly discount rates given in table 2 have been adjusted to that procedure. Table 2 is organized as follows. In the left column different constant discount rates (δ) are listed ranging from 7.5% to -0.5% . To calculate the present values conventionally, these constant rates are used to discount all external effects E_t according to the exponential formulation (in discrete time-steps):

$$(2) \quad PV_0 = \sum_{t=0}^{600} \frac{E_t}{(1 + \delta_t)^t}$$

Present value calculations in the GAD-regime have been done according to equation (1) (see above).

Best Guess			GAD		Constant Discounting	
Discount Rate	intra	inter	Bioreactor	Dry Tomb	Bioreactor	Dry Tomb
7.5%	4.5%	3.0%	15.76	9.77	14.93	8.68
6.5%	4.5%	2.0%	18.59	12.33	17.15	10.17
6.0%	3.0%	3.0%	19.25	12.24	18.42	11.07
5.5%	4.5%	1.0%	23.30	18.09	19.82	12.09
5.5%	2.5%	3.0%	20.63	13.26	19.82	12.09
4.5%	4.5%	0.0%	46.88	60.16	23.14	14.66
4.0%	2.0%	2.0%	26.69	18.97	25.12	16.32
4.0%	3.0%	1.0%	29.43	24.10	25.12	16.32
4.0%	3.5%	0.5%	34.00	32.93	25.12	16.32
4.0%	4.0%	0.0%	51.81	67.64	25.12	16.32
4.0%	4.5%	-0.5%	158.95	276.83	25.12	16.32
3.5%	0.5%	3.0%	27.74	18.94	27.39	18.36
3.5%	4.5%	-1.0%	1185.17	2278.33	27.39	18.36
3.0%	1.0%	2.0%	31.36	23.24	30.05	20.93
3.0%	2.0%	1.0%	34.94	30.01	30.05	20.93
3.0%	3.0%	0.0%	64.51	87.58	30.05	20.93
3.0%	4.0%	-1.0%	1367.27	2631.39	30.05	20.93
2.0%	0.5%	1.5%	39.01	32.35	37.34	29.21
2.0%	1.0%	1.0%	42.23	38.51	37.34	29.21
2.0%	1.5%	0.5%	50.51	54.58	37.34	29.21
2.0%	2.0%	0.0%	82.91	117.80	37.34	29.21
2.0%	2.5%	-0.5%	278.08	498.94	37.34	29.21
2.0%	3.0%	-1.0%	1877.80	3622.62	37.34	29.21
1.5%	0.5%	1.0%	46.82	44.23	43.00	36.88
1.5%	1.0%	0.5%	56.70	63.42	43.00	36.88
1.5%	1.5%	0.0%	95.39	138.94	43.00	36.88
1.5%	2.0%	-0.5%	328.52	594.23	43.00	36.88
1.5%	2.5%	-1.0%	2239.51	4325.71	43.00	36.88
0.5%	0.5%	0.0%	130.84	200.83	73.90	89.62
-0.5%	0.5%	-1.0%	5176.63	10046.72	867.03	1629.97

Table 2: Present value calculations of net external costs, dry tomb and bioreactor landfills, best guess, €/t.

In table 2, bold italic figures in the columns indicate lower present values of net external costs in our two different discounting regimes. Constant discounting mainly shows the dry tomb technology as the efficient one producing lower present values of external costs. Only in two very extreme cases with very low constant discount rates (0.5% and -0.5%) the bioreactor type landfill is more efficient than the dry-tomb one. However, using GAD the bioreactor landfill has lower present values of external costs compared to the dry tomb case in 14 more cases. Altogether, the bioreactor landfill is more efficient than the dry tomb one in 16 cases in our best guess scenario (19 times in the best case scenario, 16 times in the worst case scenario, see Annexes B1 and B2). The efficiency of our two different landfill types significantly depend on the assumed discounting regime even for identical initial discount

rates. Thus, our small example shows clearly that the choice of the discounting regime is a strategic decision to calculate present values of external costs.

The efficiency judgements mainly depend on the size of the growth rate (intergenerational discount rate). The lower it is, the more favourable the bioreactor type becomes. When there is high growth, the dry tomb landfill is the better solution. In the assumed 600-year context, a real growth rate even for industrialized countries of 1% p.a. is a quite meaningful assumption (Maddison, 2001). Higher annual growth rates have never been observed in comparable time horizons. Thus, all cases where growth rates up to 1% are used seem to be realistic, and, this leads to the conclusion that the bioreactor-type landfill is the more suitable with respect to sustainability compared to the dry-tomb technology.

Another finding is that GAD allows for a more detailed analysis: While constant discounting always leads to the same present values and, therefore, the same efficiency result using one specific discount rate (e.g., 3%), this is not the case applying GAD: Generally, a switch in efficiency is observable whenever the growth discount rate is lowered. In the 3%-case, GAD shows that the bioreactor- as well as the dry tomb-landfill is favourable in two cases each. Thus, the two different discounting techniques would generate very different suggestions with respect to technological choice in municipal solid waste management.

It can be stated that the above criticized moral judgement of neoclassical theory – an inherent bias at the expense of future living generations and favouring current living ones – applying the constant discounting regime becomes relevant and predetermines the efficiency of our two landfill technologies. This is obviously in sharp contradiction to the normative requirement of equal treatment of all affected generations. Therefore, we want to demonstrate the “unsustainability” of constant discounting by calculating “sustainability gaps” which become relevant whenever one decides to use the constant discounting regime in social cost-benefit analyses.

4 Sustainability gaps (with respect to intergenerational fairness)

4.1 General concept

GAD is explicitly based upon the basic utilitarian requirement of equal treatment of all affected generations. Thus, it can be interpreted as a reference discounting technique which allows for sustainable decision-making and is very easily applicable in cost-benefit analyses. The present values calculated using GAD must be produced whenever alternative techniques would be applied to identify whether they are in accordance with the sustainability criteria of intertemporal fairness.

Given the GAD present value, one is able to solve equation (2) – constant discounting – with respect to the now endogenous discount rate d to calculate which equivalent constant discount rate d generates exactly the GAD present value. The difference in constant discount rates

between the original and the modified calculation can be interpreted as a “sustainability gap” of constant discounting compared to sustainable discounting, in fact GAD. Thus, we ask which constant discount rate is able to calculate the same present value as is computed by the GAD. For example, we assume an original discount rate of 4.5% – which is split up into 4.5% intragenerational discount rate and 0% intergenerational discount rate. The GAD present value in the bioreactor best guess case is given with 46.88 €/t (see table 2). To calculate the sustainability gap of constant discounting in that specific case, we need to know, which constant discount rate exactly produces the sustainable present value of 46.88. This means we have to solve the following equation (3) for d_t which is done numerically.

$$(3) \quad 46.88 \text{ €/t} = \sum_{t=0}^{600} \frac{E_t}{(1+d_t)^t} \Leftrightarrow d_t = 1.25\%.$$

A constant discount rate of 1.25% leads to a present value of external costs of 46.88 €/t. Compared to the original discount rate of 4.5% this figure is significantly lower. In this special case, a sustainability gap of the constant discounting regime can be quantified with 3.25% per year (4.5%-1.25%). In other words: A social cost-benefit analysis in the constant discounting regime uses a discount rate which is 3.25% p.a. higher (in absolute terms) as it should be the case in the sustainable discounting regime. Thus, in each year a bias of 3.25% (in absolute terms) at the expense of future living generations exists. The exponential development of this large difference need not be emphasized.

The sustainability gap can alternatively be illustrated in a relative way by calculating the ratio of the absolute difference of the original discount rate (4.5% in our example) and the GAD-equivalent constant discount rate (1.25% in our example, leading to 3.25% in the numerator) divided by the GAD-equivalent constant discount rate of 1.25%. In our example a ratio of 2.6 (or 260%) results which means that the yearly constant discount rate is by the factor 2.6 too high in sustainability terms.

4.2 Sustainability gaps in waste management: Definition and Results

After having shown how to calculate GAD-equivalent constant discount rates we want to define the sustainability gap as the difference between the original constant discount rate and the GAD-equivalent ones:

$$(4) \quad \begin{aligned} &\text{absolute sustainability gap} \\ &= \text{original constant discount rate} - \text{GAD-equivalent constant discount rate.} \end{aligned}$$

We prefer to calculate absolute differences compared to relative ones because it more illustrative and easier to interpret compared to the relative notation. Whenever calculating relative sustainability gaps, the ethical reference is taken into account twofold which complicates its understanding without having additional information. Table 3 gives the absolute sustainability gaps in the best guess scenario. Tables C1 and C2 in the Annex depict the respective figures in the best case and the worst case scenarios.

Best Guess			GAD equivalent constant discount rate		Sustainability Gap (in absolute percentages)	
Discount Rate	intra	inter	Bioreactor	Dry Tomb	Bioreactor	Dry Tomb
7.5%	4.5%	3.0%	7.103%	6.750%	0.3973%	0.7498%
6.5%	4.5%	2.0%	5.936%	5.391%	0.5639%	1.1095%
6.0%	3.0%	3.0%	5.699%	5.433%	0.3008%	0.5665%
5.5%	4.5%	1.0%	4.456%	3.559%	1.0439%	1.9407%
5.5%	2.5%	3.0%	5.236%	5.005%	0.2645%	0.4955%
4.5%	4.5%	0.0%	1.253%	0.826%	3.2467%	3.6743%
4.0%	2.0%	2.0%	3.646%	3.369%	0.3536%	0.6315%
4.0%	3.0%	1.0%	3.109%	2.532%	0.8906%	1.4679%
4.0%	3.5%	0.5%	2.315%	1.725%	1.6848%	2.2751%
4.0%	4.0%	0.0%	1.020%	0.715%	2.9804%	3.2847%
4.0%	4.5%	-0.5%	0.012%	-0.020%	3.9876%	4.0204%
3.5%	0.5%	3.0%	3.429%	3.376%	0.0712%	0.1241%
3.5%	4.5%	-1.0%	-0.573%	-0.576%	4.0729%	4.0756%
3.0%	1.0%	2.0%	2.784%	2.646%	0.2157%	0.3543%
3.0%	2.0%	1.0%	2.278%	1.935%	0.7224%	1.0654%
3.0%	3.0%	0.0%	0.656%	0.515%	2.3441%	2.4849%
3.0%	4.0%	-1.0%	-0.605%	-0.607%	3.6053%	3.6074%
2.0%	0.5%	1.5%	1.831%	1.763%	0.1685%	0.2368%
2.0%	1.0%	1.0%	1.557%	1.422%	0.4430%	0.5778%
2.0%	1.5%	0.5%	1.074%	0.930%	0.9256%	1.0705%
2.0%	2.0%	0.0%	0.393%	0.337%	1.6065%	1.6633%
2.0%	2.5%	-0.5%	-0.192%	-0.202%	2.1921%	2.2016%
2.0%	3.0%	-1.0%	-0.675%	-0.676%	2.6752%	2.6764%
1.5%	0.5%	1.0%	1.257%	1.200%	0.2434%	0.2997%
1.5%	1.0%	0.5%	0.849%	0.774%	0.6510%	0.7258%
1.5%	1.5%	0.0%	0.287%	0.254%	1.2135%	1.2465%
1.5%	2.0%	-0.5%	-0.244%	-0.250%	1.7436%	1.7499%
1.5%	2.5%	-1.0%	-0.713%	-0.714%	2.2131%	2.2140%
0.5%	0.5%	0.0%	0.102%	0.096%	0.3979%	0.4044%
-0.5%	0.5%	-1.0%	-0.887%	-0.887%	0.3867%	0.3868%

Table 3: GAD-equivalent discount rates and sustainability gaps in the best guess scenario.

It can be seen in table 3 that all GAD-equivalent constant discount rates are absolutely lower compared to the original ones. From the perspective of sustainability constant discounting always uses too high values to calculate present values and the requirement of equal treatment

is not taken seriously. Ramseys (1928) critical statement using positive utility discount rates can, therefore, be fully confirmed using table 3 as well as tables C1 as well as C2 in the Annex.

The first interesting finding of our calculations is that there are – in some cases – enormous differences in yearly discount rates. The maximum in a – not very realistic case – is approximately 4% which factually describes the difference of yearly discount rates. Obviously, this has significant impacts on the present value calculations and the conclusions which can be drawn applying social cost-benefit analyses. In all other cases the sustainability gap is not negligible especially when one is beware of the fact that this gap measures yearly discount rates which are applied in a 600-year time horizon. The lowest sustainability gap in the best guess scenario is given with 0.07% (in absolute terms). The isolated compound interest effect of this very low figure in a 600-years calculation is still quite high: The overall return is about 52% in a 600 year planning horizon. Obviously, whenever the sustainability gaps become larger, the overall return will be much higher as well and the differences in present values become much more distinct.

Table 3 works out, that the sustainability gap becomes larger when there is negative growth in the future compared to these cases where there is positive growth. Here, future generations would be worse off compared to current living ones. Thus, additional consumption units tomorrow are of higher social value than consumption units today. This must be taken into account by discounting negatively, which is usually not done in the constant discounting regime. This clearly demonstrates the unsustainable character of constant discounting once again.

It has to be emphasized that the GAD-equivalent discount rate could also be negative which only happens when there is a negative growth rate, of course. Theoretically, the Euler equation could become negative as well whenever the negative growth rate (εg) overcompensates the positive myopic discount rate (ρ). However, this is usually not assumed in theoretical as well as in empirical economic studies. Some authors assume negative growth rates, but still use positive discount rates because the myopic discount rate is set higher (in absolute terms) compared to the growth rate. In these cases constant discounting implicitly assumes that future generations are wealthier than current living ones which – in this specific framework – is not true at all. Using GAD instead, the wealth implications are taken into account by using only the growth rate for intergenerational discounting and refuse discounting with the myopic rate whenever intergenerational comparisons have to be carried out.

The most important application of the sustainability gap which has been defined above is to use it as a measure to check the sustainability of projects which are calculated using a constant discount rate – or any other discounting technique which is inherently “unsustainable”. The higher the sustainability gap becomes the more “unsustainable” the decision has been and vice versa. Additionally, one is able to work out an indicator for sustainable or unsustainable decision-making of governments or other project managers.

To summarize, the application of the constant discounting regime inherently lacks in fulfilling fundamental sustainability criteria. Thus, using GAD in long-term cost-benefit analyses enables a non-distorting decision where all affected generations are of equal value to the beginning of the lifetime of a specific project.

5 Conclusions

It has been shown how ethical aspects can be implemented in decision-support tools like cost-benefit analyses via discounting in the framework of a GAD-regime. The application of the sustainable discounting procedure GAD for the judgement of the efficiency of two landfill technologies (dry tomb and bioreactor) produces results which are in sharp contrast to the results of constant unsustainable discounting. Not-surprisingly, long-term effects do not play a decisive role in the constant discounting regime whereas they are taken more into account in the GAD-regime. Our analysis leads us to two different findings: With respect to the landfill example we are able to show that the bioreactor-type is generally more efficient than its alternative, the dry tomb-type, especially when relatively low long-term growth rates exist, i.e., up to 1% p.a. Secondly, we introduce a measure to check the sustainability of long-term public projects, a “sustainability gap”: Having a look at the project-specific discount rate and calculating a sustainability gap, we are able to judge to what extent sustainability criteria have been considered in the planning process of these projects. High sustainability gaps indicate that the project planner does not take the requirement of intergenerational fairness into account whereas low ones show the opposite.

Moreover, the sustainable discounting technique GAD can be applied to many other public projects where long-term effects have to be dealt with: hazardous and nuclear waste landfills, energy supply and demand, global warming, pension systems, etc. GAD may suggest – possibly radical – policy modifications and a sounder judgement of their sustainable character in comparison to the constant discounting regime.

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Annex A2: Temporal distribution of bioreactor landfill externalities

Temporal distribution of externalities in bioreactor-type-landfills (Euros per tonne and decade)															
Physical non perceived costs (3 levels of leachate emissions and natural time lags 1, 10, 50 decades)				Disamenities (induced traffic, animals, dust, odours)			Global warming costs (due to methane leakage)			Avoided pollution benefits from energy plants (due to methane energy use)			Sum of all external costs		
Decades	Damage Costs			Best case	Best guess	Worst case	Best case	Best guess	Worst case	Best case	Best guess	Worst case	Best case	Best guess	Worst case
	Best case	Best guess	Worst case												
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	5	20	50	0.271	0.625	3.4489	3	1.5	0.3	2.271	19.125	53.1489
2	0	0	0.1	5	20	50	0.523	2.9	7.64	3	1.5	0.3	2.523	21.4	57.44
3	0	0	0.1	0.5	2	5	0.18	1.2	3.2	0	0	0	0.68	3.2	8.3
4	0	0	0.1	0.5	2	5	0.081	0.5	1.4	0	0	0	0.581	2.5	6.5
5	0	0	0.1	0.5	2	5	0.04	0.25	0.7	0	0	0	0.54	2.25	5.8
6	0	0	0.1	0.5	2	5	0.02	0.15	0.35	0	0	0	0.52	2.15	5.45
7	0	0	0.5	0.5	2	5	0.01	0.05	0.15	0	0	0	0.51	2.05	5.65
8	0	0	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2	5.5
9	0	0	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2	5.5
10	0	0	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2	5.5
11	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
12	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
13	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
14	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
15	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
16	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
17	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
18	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
19	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
20	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
21	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
22	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
23	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
24	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
25	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
26	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
27	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
28	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
29	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
30	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
31	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
32	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
33	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
34	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
35	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
36	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
37	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
38	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
39	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
40	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
41	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
42	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
43	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
44	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
45	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
46	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
47	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
48	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
49	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
50	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
51	0.1	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.6	2.1	5.5
52	0.1	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.6	2.1	5.5
53	0.1	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.6	2.1	5.5
54	0.1	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.6	2.1	5.5
55	0.1	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.6	2.1	5.5
56	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
57	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
58	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5
59	0	0.1	0.5	0.5	2	5	0	0	0	0	0	0	0.5	2.1	5.5

Annex B1: Present value calculations of net external costs, dry tomb and bioreactor landfills, best case, €/t.

Best Case			GAD		Constant Discounting	
Discount Rate	intra	inter	Bioreactor	Dry Tomb	Bioreactor	Dry Tomb
7.5%	4.5%	3.0%	1.99	1.50	1.83	1.35
6.5%	4.5%	2.0%	2.42	1.90	2.12	1.56
6.0%	3.0%	3.0%	2.46	1.85	2.29	1.68
5.5%	4.5%	1.0%	3.26	2.99	2.49	1.82
5.5%	2.5%	3.0%	2.65	1.99	2.49	1.82
4.5%	4.5%	0.0%	8.63	12.86	2.95	2.16
4.0%	2.0%	2.0%	3.59	2.87	3.24	2.39
4.0%	3.0%	1.0%	4.22	3.99	3.24	2.39
4.0%	3.5%	0.5%	5.31	6.06	3.24	2.39
4.0%	4.0%	0.0%	9.64	14.51	3.24	2.39
4.0%	4.5%	-0.5%	36.28	66.50	3.24	2.39
3.5%	0.5%	3.0%	3.66	2.78	3.59	2.67
3.5%	4.5%	-1.0%	296.61	570.37	3.59	2.67
3.0%	1.0%	2.0%	4.30	3.50	4.00	3.05
3.0%	2.0%	1.0%	5.14	4.99	4.00	3.05
3.0%	3.0%	0.0%	12.30	18.92	4.00	3.05
3.0%	4.0%	-1.0%	342.49	658.92	4.00	3.05
2.0%	0.5%	1.5%	5.65	5.06	5.26	4.39
2.0%	1.0%	1.0%	6.41	6.46	5.26	4.39
2.0%	1.5%	0.5%	8.39	10.26	5.26	4.39
2.0%	2.0%	0.0%	16.28	25.70	5.26	4.39
2.0%	2.5%	-0.5%	64.86	120.54	5.26	4.39
2.0%	3.0%	-1.0%	471.18	907.51	5.26	4.39
1.5%	0.5%	1.0%	7.24	7.47	6.33	5.80
1.5%	1.0%	0.5%	9.60	12.03	6.33	5.80
1.5%	1.5%	0.0%	19.03	30.48	6.33	5.80
1.5%	2.0%	-0.5%	77.08	143.81	6.33	5.80
1.5%	2.5%	-1.0%	562.35	1083.82	6.33	5.80
0.5%	0.5%	0.0%	27.01	44.60	13.12	17.38
-0.5%	0.5%	-1.0%	1302.33	2518.27	208.38	397.92

Annex B2: Present value calculations of net external costs, dry tomb and bioreactor landfills, worst case, €/t.

Worst Case			GAD		Constant Discounting	
Discount Rate	intra	inter	Bioreactor	Dry Tomb	Bioreactor	Dry Tomb
7.5%	4.5%	3.0%	43.12	26.70	40.91	23.79
6.5%	4.5%	2.0%	50.74	33.59	46.91	27.86
6.0%	3.0%	3.0%	52.56	33.42	50.36	30.29
5.5%	4.5%	1.0%	63.37	48.75	54.16	33.08
5.5%	2.5%	3.0%	56.30	36.20	54.16	33.08
4.5%	4.5%	0.0%	125.51	156.97	63.12	40.06
4.0%	2.0%	2.0%	72.63	51.54	68.47	44.56
4.0%	3.0%	1.0%	79.86	64.79	68.47	44.56
4.0%	3.5%	0.5%	91.88	87.46	68.47	44.56
4.0%	4.0%	0.0%	138.59	176.37	68.47	44.56
4.0%	4.5%	-0.5%	419.27	711.96	68.47	44.56
3.5%	0.5%	3.0%	75.52	51.59	74.59	50.06
3.5%	4.5%	-1.0%	3107.31	5837.44	74.59	50.06
3.0%	1.0%	2.0%	85.20	63.04	81.74	57.00
3.0%	2.0%	1.0%	94.66	80.51	81.74	57.00
3.0%	3.0%	0.0%	172.22	228.01	81.74	57.00
3.0%	4.0%	-1.0%	3584.46	6741.82	81.74	57.00
2.0%	0.5%	1.5%	105.71	87.19	101.29	79.06
2.0%	1.0%	1.0%	114.19	103.06	101.29	79.06
2.0%	1.5%	0.5%	135.94	144.27	101.29	79.06
2.0%	2.0%	0.0%	220.90	306.18	101.29	79.06
2.0%	2.5%	-0.5%	732.18	1282.00	101.29	79.06
2.0%	3.0%	-1.0%	4922.11	9280.79	101.29	79.06
1.5%	0.5%	1.0%	126.48	118.19	116.39	99.26
1.5%	1.0%	0.5%	152.42	167.40	116.39	99.26
1.5%	1.5%	0.0%	253.86	360.77	116.39	99.26
1.5%	2.0%	-0.5%	864.57	1526.44	116.39	99.26
1.5%	2.5%	-1.0%	5869.77	11081.65	116.39	99.26
0.5%	0.5%	0.0%	347.37	520.42	198.10	235.71
-0.5%	0.5%	-1.0%	13564.01	25733.68	2276.67	4181.18

Annex C1: GAD-equivalent discount rates and sustainability gaps in the best case scenario.

Best Case			GAD equivalent constant discount rate		Sustainability Gap (in absolute percentages)	
Discount Rate	intra	inter	Bioreactor	Dry Tomb	Bioreactor	Dry Tomb
7.5%	4.5%	3.0%	6.9353%	6.7629%	0.5647%	0.7371%
6.5%	4.5%	2.0%	5.6683%	5.2443%	0.8317%	1.2557%
6.0%	3.0%	3.0%	5.5689%	5.3930%	0.4311%	0.6070%
5.5%	4.5%	1.0%	3.9738%	3.0648%	1.5262%	2.4352%
5.5%	2.5%	3.0%	5.1208%	4.9529%	0.3792%	0.5471%
4.5%	4.5%	0.0%	0.9357%	0.6864%	3.5643%	3.8136%
4.0%	2.0%	2.0%	3.4980%	3.2170%	0.5020%	0.7830%
4.0%	3.0%	1.0%	2.7770%	2.2147%	1.2230%	1.7853%
4.0%	3.5%	0.5%	1.9666%	1.4347%	2.0334%	2.5653%
4.0%	4.0%	0.0%	0.7935%	0.6071%	3.2065%	3.3929%
4.0%	4.5%	-0.5%	-0.0168%	-0.0393%	4.0168%	4.0393%
3.5%	0.5%	3.0%	3.4006%	3.3501%	0.0994%	0.1499%
3.5%	4.5%	-1.0%	-0.5799%	-0.5799%	4.0799%	4.0799%
3.0%	1.0%	2.0%	2.7070%	2.5624%	0.2930%	0.4376%
3.0%	2.0%	1.0%	2.0708%	1.7479%	0.9292%	1.2521%
3.0%	3.0%	0.0%	0.5513%	0.4536%	2.4487%	2.5464%
3.0%	4.0%	-1.0%	-0.6115%	-0.6112%	3.6115%	3.6112%
2.0%	0.5%	1.5%	1.7908%	1.7205%	0.2092%	0.2795%
2.0%	1.0%	1.0%	1.4730%	1.3197%	0.5270%	0.6803%
2.0%	1.5%	0.5%	0.9769%	0.8572%	1.0231%	1.1428%
2.0%	2.0%	0.0%	0.3508%	0.3067%	1.6492%	1.6933%
2.0%	2.5%	-0.5%	-0.2023%	-0.2091%	2.2023%	2.2091%
2.0%	3.0%	-1.0%	-0.6803%	-0.6795%	2.6803%	2.6795%
1.5%	0.5%	1.0%	1.2212%	1.1668%	0.2788%	0.3332%
1.5%	1.0%	0.5%	0.7985%	0.7343%	0.7015%	0.7657%
1.5%	1.5%	0.0%	0.2613%	0.2341%	1.2387%	1.2659%
1.5%	2.0%	-0.5%	-0.2511%	-0.2554%	1.7511%	1.7554%
1.5%	2.5%	-1.0%	-0.7177%	-0.7168%	2.2177%	2.2168%
0.5%	0.5%	0.0%	0.0968%	0.0910%	0.4032%	0.4090%
-0.5%	0.5%	-1.0%	-0.8896%	-0.8883%	0.3896%	0.3883%

Annex C2: GAD-equivalent discount rates and sustainability gaps in the worst case scenario.

Worst Case			GAD equivalent constant discount rate		Sustainability Gap (in absolute percentages)	
Discount Rate	intra	inter	Bioreactor	Dry Tomb	Bioreactor	Dry Tomb
7.5%	4.5%	3.0%	7.1114%	6.7618%	0.3886%	0.7382%
6.5%	4.5%	2.0%	5.9474%	5.4148%	0.5526%	1.0852%
6.0%	3.0%	3.0%	5.7051%	5.4431%	0.2949%	0.5569%
5.5%	4.5%	1.0%	4.4758%	3.6095%	1.0242%	1.8905%
5.5%	2.5%	3.0%	5.2404%	5.0135%	0.2596%	0.4865%
4.5%	4.5%	0.0%	1.2792%	0.8444%	3.2208%	3.6556%
4.0%	2.0%	2.0%	3.6518%	3.3827%	0.3482%	0.6173%
4.0%	3.0%	1.0%	3.1235%	2.5653%	0.8765%	1.4347%
4.0%	3.5%	0.5%	2.4225%	1.7605%	1.5775%	2.2395%
4.0%	4.0%	0.0%	1.0384%	0.7294%	2.9616%	3.2706%
4.0%	4.5%	-0.5%	0.0146%	-0.0186%	3.9854%	4.0186%
3.5%	0.5%	3.0%	3.4298%	3.3783%	0.0702%	0.1217%
3.5%	4.5%	-1.0%	-0.5727%	-0.5755%	4.0727%	4.0755%
3.0%	1.0%	2.0%	2.7871%	2.6534%	0.2129%	0.3466%
3.0%	2.0%	1.0%	2.2872%	1.9546%	0.7128%	1.0454%
3.0%	3.0%	0.0%	0.6647%	0.5226%	2.3353%	2.4774%
3.0%	4.0%	-1.0%	-0.6051%	-0.6073%	3.6051%	3.6073%
2.0%	0.5%	1.5%	1.8333%	1.7674%	0.1667%	0.2326%
2.0%	1.0%	1.0%	1.5615%	1.4307%	0.4385%	0.5693%
2.0%	1.5%	0.5%	1.0813%	0.9382%	0.9187%	1.0618%
2.0%	2.0%	0.0%	0.3970%	0.3401%	1.6030%	1.6599%
2.0%	2.5%	-0.5%	-0.1914%	-0.2009%	2.1914%	2.2009%
2.0%	3.0%	-1.0%	-0.6751%	-0.6764%	2.6751%	2.6764%
1.5%	0.5%	1.0%	1.2587%	1.2040%	0.2413%	0.2960%
1.5%	1.0%	0.5%	0.8527%	0.7790%	0.6473%	0.7210%
1.5%	1.5%	0.0%	0.2886%	0.2556%	1.2114%	1.2444%
1.5%	2.0%	-0.5%	-0.2431%	-0.2495%	1.7431%	1.7495%
1.5%	2.5%	-1.0%	-0.7131%	-0.7140%	2.2131%	2.2140%
0.5%	0.5%	0.0%	0.1025%	0.0961%	0.3975%	0.4039%
-0.5%	0.5%	-1.0%	-0.8867%	-0.8868%	0.3867%	0.3868%

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